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Charmonium Production *

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ABSTRACT

Theoretical analyses of the results on quarkonium production at large transverse momentum (p_T) in $p\bar{p}$ collisions, at the Tevatron have revealed two novel features of the physics of quarkonium production : 1) the contribution of fragmentation of gluons and charm quarks to the cross-section at large p_T, and 2) the importance of colour octet components of the quarkonium wave-function. I discuss the theoretical developments which have contributed to a reasonably consistent picture of quarkonium production at the Tevatron, and discuss large-p_T J/ψ production at HERA and at LHC as important tests of the fragmentation picture. I also discuss our recent analysis of J/ψ production cross-sections at fixed-target energies, where we find that the energy dependence of the p_T-integrated cross-sections for both pp and $\pi^- - p$ collisions is reasonably well reproduced, when the colour-octet components are included.

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Quarkonium production has conventionally been described in the colour-singlet model [1, 2], wherein a heavy-quark pair produced via parton-fusion processes is projected onto a physical quarkonium state using a colour-singlet projection and an appropriate spin-projection. This model has been successfully applied [2] to describe large-p_T J/ψ production in the ISR experiment. However, the inclusive J/ψ production cross-section measured by the CDF experiment at the Tevatron [3] turned out to be an order of magnitude larger than the prediction of the colour-singlet model.

It was realised [4] that in addition to the parton fusion contributions, fragmentation of gluons and charm quarks could be an important source of large-p_T J/ψ production at high energies. This is computed by factorising the cross-section for the process $AB \to (J/\psi, \chi_i)X$ (where A, B denote hadrons) into a part containing the hard-scattering cross-section for producing a parton of large-p_T but zero virtuality, and a part which specifies the fragmentation of the gluon or the charm quark into the required charmonium state. The fragmentation function can be computed perturbatively, in the same spirit as in the colour-singlet model. This yields the fragmentation function at an initial scale μ_0 which is of the order of m_c, and large logarithms in p_T/m_c which appear are resummed using the Altarelli-Parisi equation. The gluon and charm fragmentation functions have been calculated [4, 5] and using these inputs it has been found [6] that the order-of-magnitude discrepancy between the theory and the CDF data can be resolved.

Another important aspect of the physics of quarkonia revealed by the analyses of the CDF data is the importance of colour-octet contributions. A systematic formulation based on non-relativistic QCD, using the factorisation method has been recently carried out [7], and in this formulation the quarkonium wave-function admits of a Fock-space expansion in powers of v, the relative velocity between the heavy quarks; for example, the χ states have the colour-singlet P-state component at leading order, but there exist additional contributions at non-leading order in v, which involve octet S-state components. The octet component allows a consistent perturbative treatment of χ decays [8], whereby the infrared divergence appearing in the colour-singlet decay amplitudes [9] can be absorbed via a wave-function renormalisation. As in the case of decays, the P-state fragmentation functions are also infra-red divergent and, hence, they include the octet component.

For S-state resonances, the octet contribution is suppressed by powers of v. Further, the S-wave amplitude is not infrared divergent. But recent measurements [10] of the direct J/ψ cross-section (i.e. not coming frm χ decays) show that the theoretical estimates are a factor 30-40 smaller. It has been suggested [11] that a colour octet component in the S-wave production coming from gluon fragmentation as originally proposed in Ref. [12], can explain this J/ψ anomaly. The value of the colour-octet matrix-element is fixed by normalising to the data. The colour-octet contribution to S-state production has also been invoked [12] to explain the large ψ' cross-section measured by CDF [3], but there can be a large contribution to this cross-section coming from the decays of radially excited P-states [13].

It is important to examine the implications of these two new physics aspects of quarkonium production *viz.*, fragmentation and the colour-octet contributions, for J/ψ and ψ' production in other processes. Important tests of fragmentation at the Tevatron can be made by studying $J/\psi + \gamma$ production at large p_T [14] and in J/ψ pair production at the Tevatron [15]. Similarly, independent tests of the S-state colour octet enhancement are important and it has been

suggested [16] that production of quarkonia in e^+e^- collisions or the measurement of the polarisation of the ψ' [17] can provide stringent tests of the colour-octet mechanisms. We discuss, in the following, results from the analyses of quarkonium production at HERA, LHC and in fixed-target experiments.

J/ψ production at large-p_T in ep collisions at HERA has been studied [18]. Only inelastic events are considered: this is obtained by making a cut on the inelasticity parameter, z, defined as

$$z = \frac{p_\psi \cdot p_p}{p_\gamma \cdot p_p}. \tag{1}$$

To ensure inelastic production of J/ψ, an upper cut on z is used, so that z is sufficiently smaller than 1. The fusion contribution to the photoproduction of J/ψ in the colour-singlet model [1] comes from photon-gluon fusion. The next-to-leading order corrections to this process [19] are in reasonable agreement with the data on integrated inelastic cross-sections from HERA. The integrated cross-sections are, however, insensitive to the fragmentation contributions, and p_T distributions need to be studied to get a handle on the fragmentation contributions.

In addition to the above fusion process, we consider the contributions from the fragmentation of gluons and charm quarks. The gluons are produced via the process $\gamma + q \to q + g$, whereas the charm quarks are produced via $\gamma + g \to c + \bar{c}$. In principle, at HERA energies we can also expect contributions from B-decays but these turn out to be dominant at values of $z \leq 0.1$ [20], and can, therefore, be eliminated by a lower z cut. We have computed the cross-sections for $\nu = 40$ and 100 GeV, We use the cuts $0.1 \leq z \leq 0.9$, as used in the ZEUS experiment at HERA [21]. We find that the fusion contribution, shown by the solid line in Fig. 1, is dominant at low p_T, but the charm quark fragmentation contribution (shown by the dashed-dotted line) becomes important for values of p_T greater than about 10 GeV. The gluon fragmentation contribution (shown by the dashed line in the figure) is smaller by over an order of magnitude throughout the range of p_T considered. The charm fragmentation subprocess is gluon-initiated and, hence, it dominates over the gluon fragmentation process. An experimental study of p_T distributions at HERA will provide us with the first direct measurement of the charm quark fragmentation functions. To enhance the fragmentation contribution, it is efficient to use a stronger upper cut on z.

At the LHC, we expect gluon fragmentation to be the most important source of charmonium production at large p_T, We have computed [22] the cross-sections for the planned LHC energy $\sqrt{s} = 14$ TeV. In Fig. 2, we present the J/ψ cross-section for a rapidity coverage $-2.5 \leq y \leq 2.5$.

We find that the cross-section for J/ψ production is completely dominated by the gluon fragmentation contribution (shown by the dotted line in Fig. 2) and is larger than the fusion contribution and the charm-quark fragmentation contribution by two orders of magnitude. The cross-section for J/ψ production is large and even at $p_T = 100$ GeV, the cross-section is as large as 0.1pb. For values of p_T so much larger than the charm quark mass, the fragmentation picture becomes exact and the experimental measurement of the J/ψ cross-section will, therefore, be a crucial test of the fragmentation picture. The LHC measurement will also be a test of the magnitude of the colour-octet contributions.

An important check of the colour-octet mechanism is provided by the comparison of the theory with p_T-integrated forward hadroproduction cross-sections from fixed-target $p - N$ and $\pi - N$ experiments [23]. A similar analysis of fixed-target hadroproduction data has also been done in Ref. [24]. The octet production cross-sections for the direct J/ψ and for the χ states

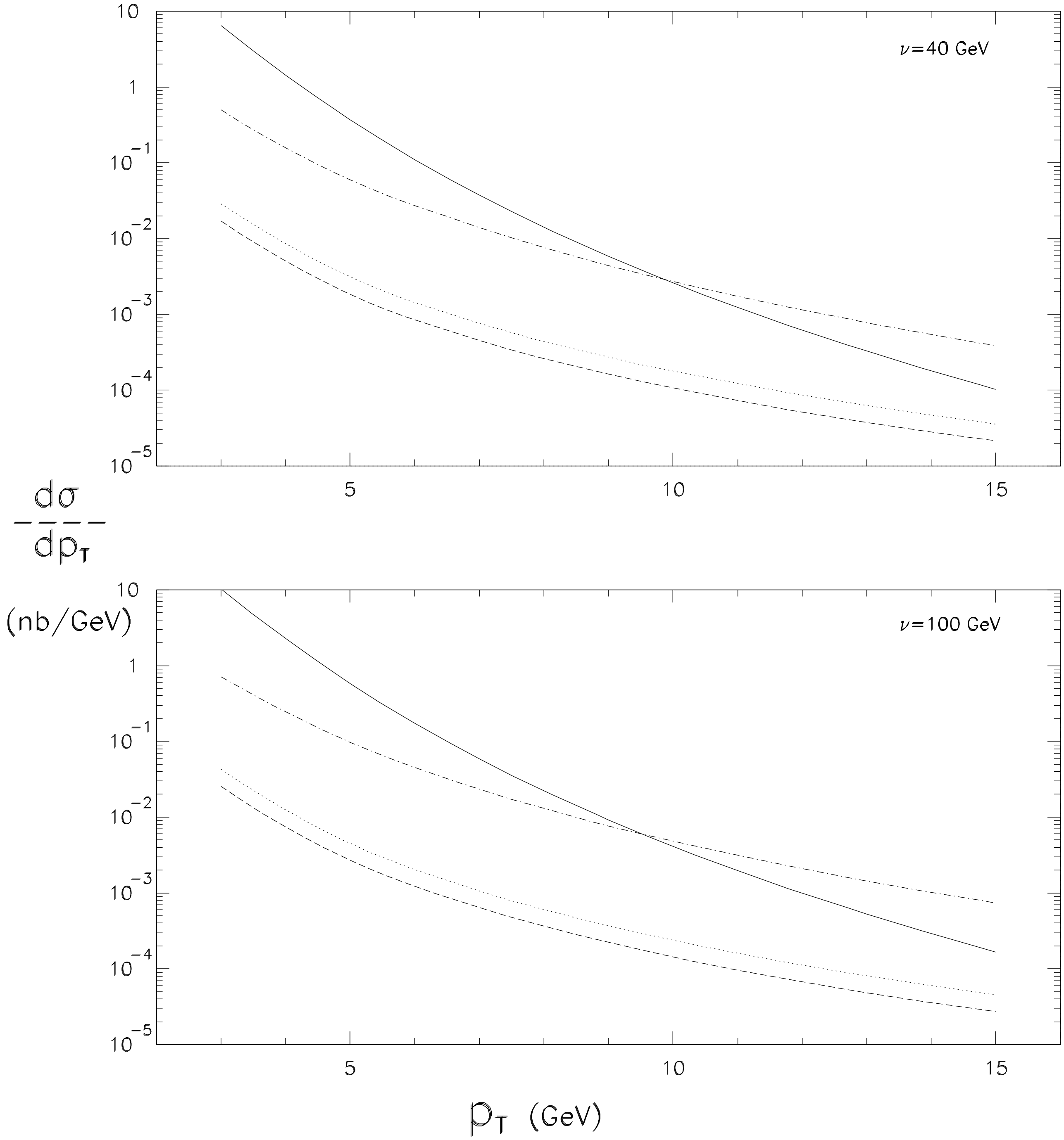

Figure 1: $d\sigma/dp_T$ (in nb/GeV) for inclusive J/ψ production at HERA for photon energy $\nu =$ 40 GeV (upper figure) and $\nu = 100$ GeV (lower figure). The solid line represents the fusion contribution and the dashed-dotted line the charm quark fragmentation contribution. The dotted and dashed lines represent the gluon fragmentation contributions with and without a colour-octet component for the S-state. The cut on the inelasticity parameter, z, is $0.1 < z <$ 0.9.

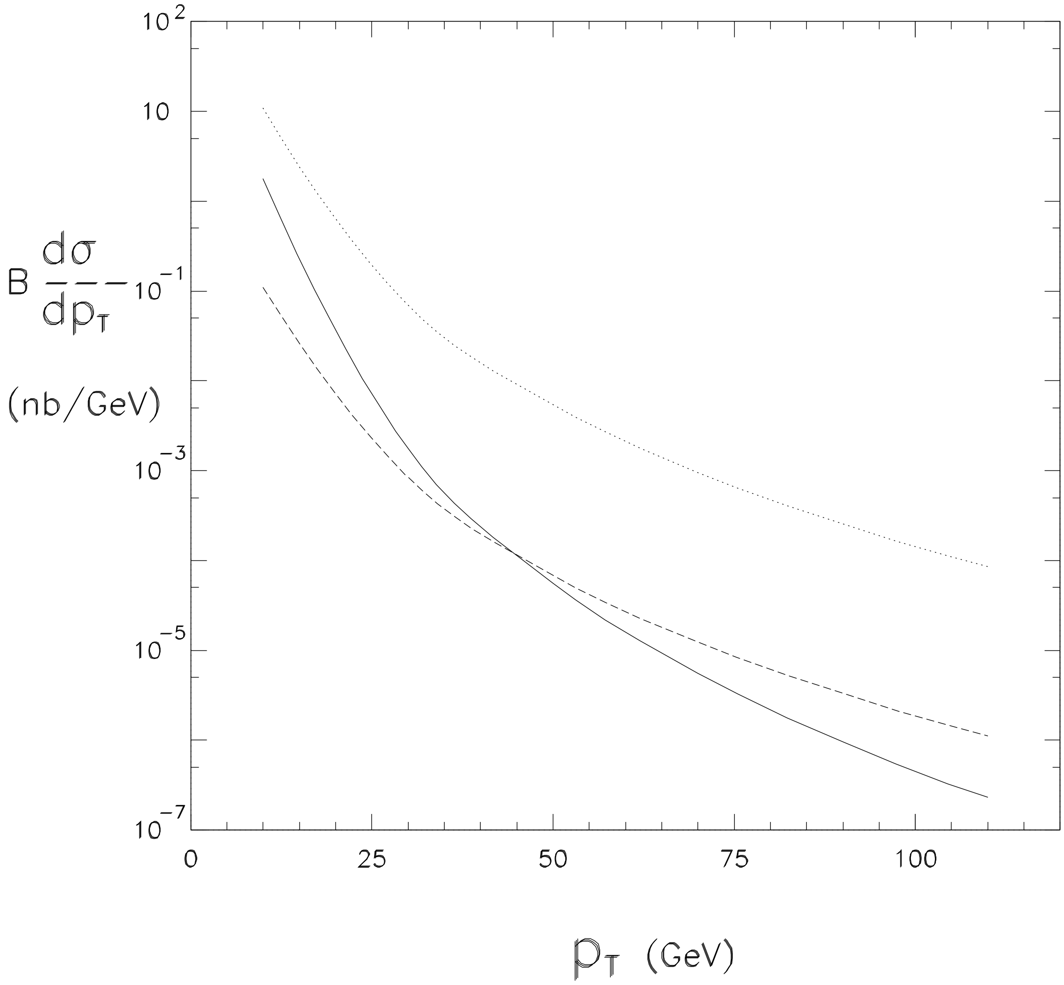

Figure 2: $Bd\sigma/dp_T$ (in nb/GeV) for J/ψ production at 14 TeV c.m. energy with $-2.5 \leq y \leq 2.5$. The solid, dashed and dotted lines represent the fusion, charm quark fragmentation and gluon fragmentation contributions.

are needed for this comparison.

The octet cross section for J/ψ is given by [25]

$$\begin{aligned}\sigma^8_{J/\psi} \ = \ & \int_{\sqrt{\tau}}^1 \tfrac{dx}{x} g_P(x) g_T(\tau/x) \frac{5\alpha_S^2\pi^3}{48m^5} \quad \left[\left\langle \mathcal{O}_8^{J/\psi}(^1S_0)\right\rangle + \frac{3}{m^2}\left\langle \mathcal{O}_8^{J/\psi}(^3P_0)\right\rangle + \frac{4}{5m^2}\left\langle \mathcal{O}_8^{J/\psi}(^3P_2)\right\rangle\right] \\ & + [\textstyle\sum_f \int_{\sqrt{\tau}}^1 \tfrac{dx}{x} q_P^f(x) \bar{q}_T^f(\tau/x) + (P \leftrightarrow T)] \dfrac{\alpha_S^2\pi^3}{54m^5}\left\langle \mathcal{O}_8^{J/\psi}(^3S_1)\right\rangle .\end{aligned} \tag{2}$$

For the octet contributions for the χ_c states, the only cross-section required is

$$\sigma^8_{\chi_J} \ = \ [\sum_f \int_{\sqrt{\tau}}^1 \frac{dx}{x} q_P^f(x) \bar{q}_T^f(\tau/x) + (P \leftrightarrow T)] \frac{\alpha_S^2\pi^3}{54m^5}\left\langle \mathcal{O}_8^{\chi_J}(^3S_1)\right\rangle . \tag{3}$$

The colour-octet matrix elements $\langle \mathcal{O}_8^{\chi_1}(^3S_1)\rangle$ and $\left\langle \mathcal{O}_8^{J/\psi}(^3S_1)\right\rangle$ have been extracted from the hadroproduction rates at the Tevatron [26]. The remaining combination of matrix elements has been extracted from photoproduction data [27]. We use this value

$$\left[\left\langle \mathcal{O}_8^{J/\psi}(^1S_0)\right\rangle + \frac{3}{m^2}\left\langle \mathcal{O}_8^{J/\psi}(^3P_0)\right\rangle + \frac{4}{5m^2}\left\langle \mathcal{O}_8^{J/\psi}(^3P_2)\right\rangle\right] \ = \ 0.020 \pm 0.001 \ \ \mathrm{GeV}^3 \tag{4}$$

in the calculations reported here[1].

Our results are shown for the two choices $m = 1.7$ GeV and a scale of $2m$, as well as $m = 1.6$ GeV and a scale of $4m$. With these inputs, we find that the $\sqrt{S}$ dependence of the integrated forward J/ψ production rates, for both pp and πp collisions, are described rather well by the model (see Figure 3). We would like to emphasise that there are no free parameters in this calculation.

In summary, we have discussed two new aspects of quarkonium physics: fragmentation and the colour-octet mechanism. We have further discussed how inelastic large-p_T photoproduction of J/ψ at HERA and large-p_T hadroproduction of J/ψ production at LHC will provide information on charm fragmentation and gluon fragmentation mechanisms, respectively. The energy dependence of p_T-integrated forward cross-sections from fixed-target $p - N$ and $\pi - N$ experiments are very well reproduced after the colour-octet Fock components have been taken into account. This is a clear indication of the neccessity of including the octet components for a complete description of quarkonium processes.

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[1]The individual matrix elements appearing in this linear combination are, however, substantially smaller than those determined by a comparison to the Tevatron large-p_T data.[26]

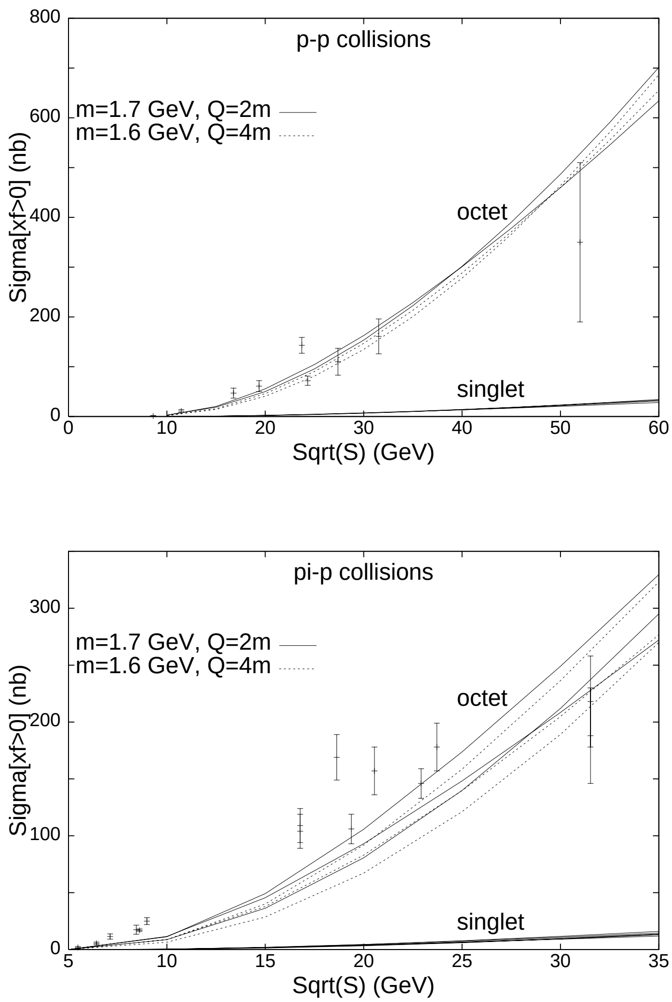

Figure 3: The colour-octet model predictions for integrated forward J/ψ hadroproduction cross sections as a function of the CM energy. For pp collisions, the two curves for each choice of m and scale Q are for the structure functions MRS D$-'$ and GRV LO. For πp collisions the three sets of structure functions are MRS D$-'$ for proton and SMRS 1 for π, MRS D$-'$ for proton and SMRS 3 for π, GRV LO for both. Note that the colour-singlet model predictions lie far below the data.

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